Supplementary Document:

Contrasting development trajectories for coastal Bangladesh to the end of century

A.N. Lázár[1], R.J. Nicholls[2], J. Hall[3], E.J. Barbour[4], A. Haque[5]

1 Geography and Environmental Science, University of Southampton, United Kingdom, a.lazar@soton.ac.uk

2 Tyndall Centre for Climate Change Research, University of East Anglia, Norwich NR4 7TJ,

United Kingdom, robert.nicholls@uea.ac.uk

3 Geography and the Environment, University of Oxford, United Kingdom, jim.hall@eci.ox.ac.uk

4 Geography and the Environment, University of Oxford, United Kingdom; CSIRO Land and Water, Canberra, Australia, Emily.Barbour@csiro.au

5 Bangladesh University of Engineering and Technology, Bangladesh, anisul.buet@gmail.com

Corresponding author: Attila N. Lazar, University of Southampton, University Road, Southampton, SO17 1BJ, United Kingdom; a.lazar@soton.ac.uk; +44-23-8059-8907

Contents

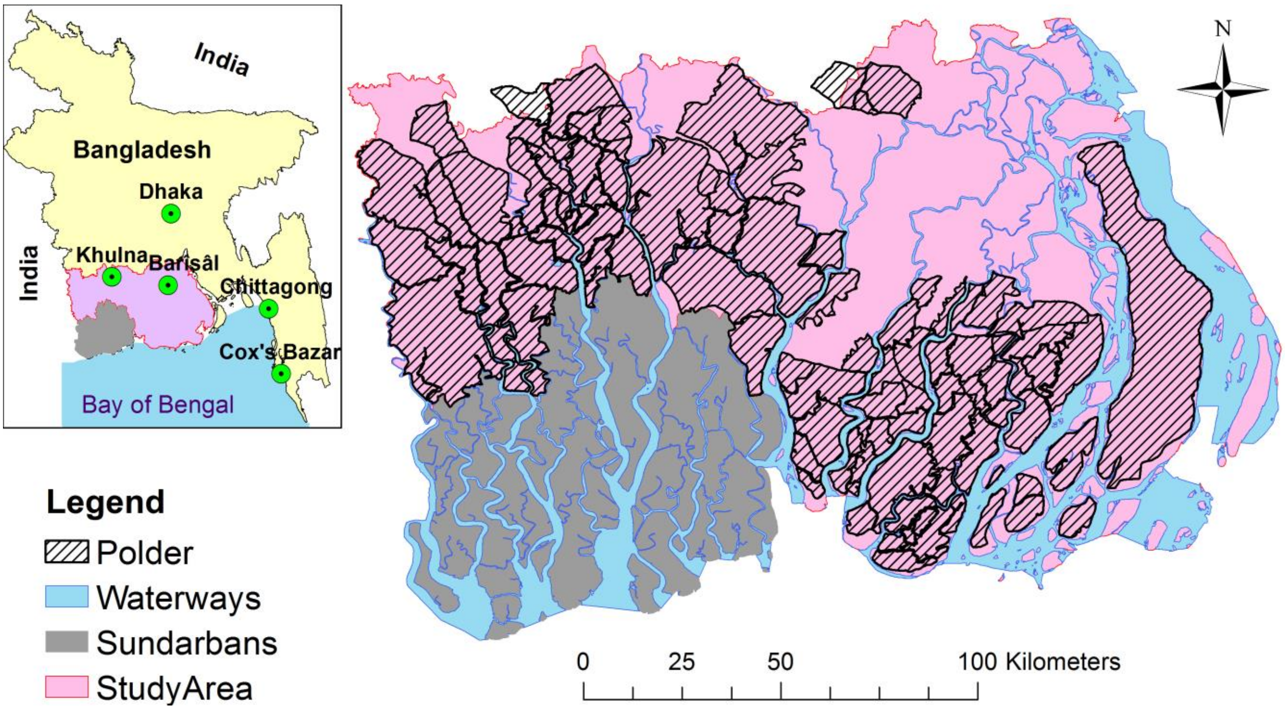


Figure S1: Study area

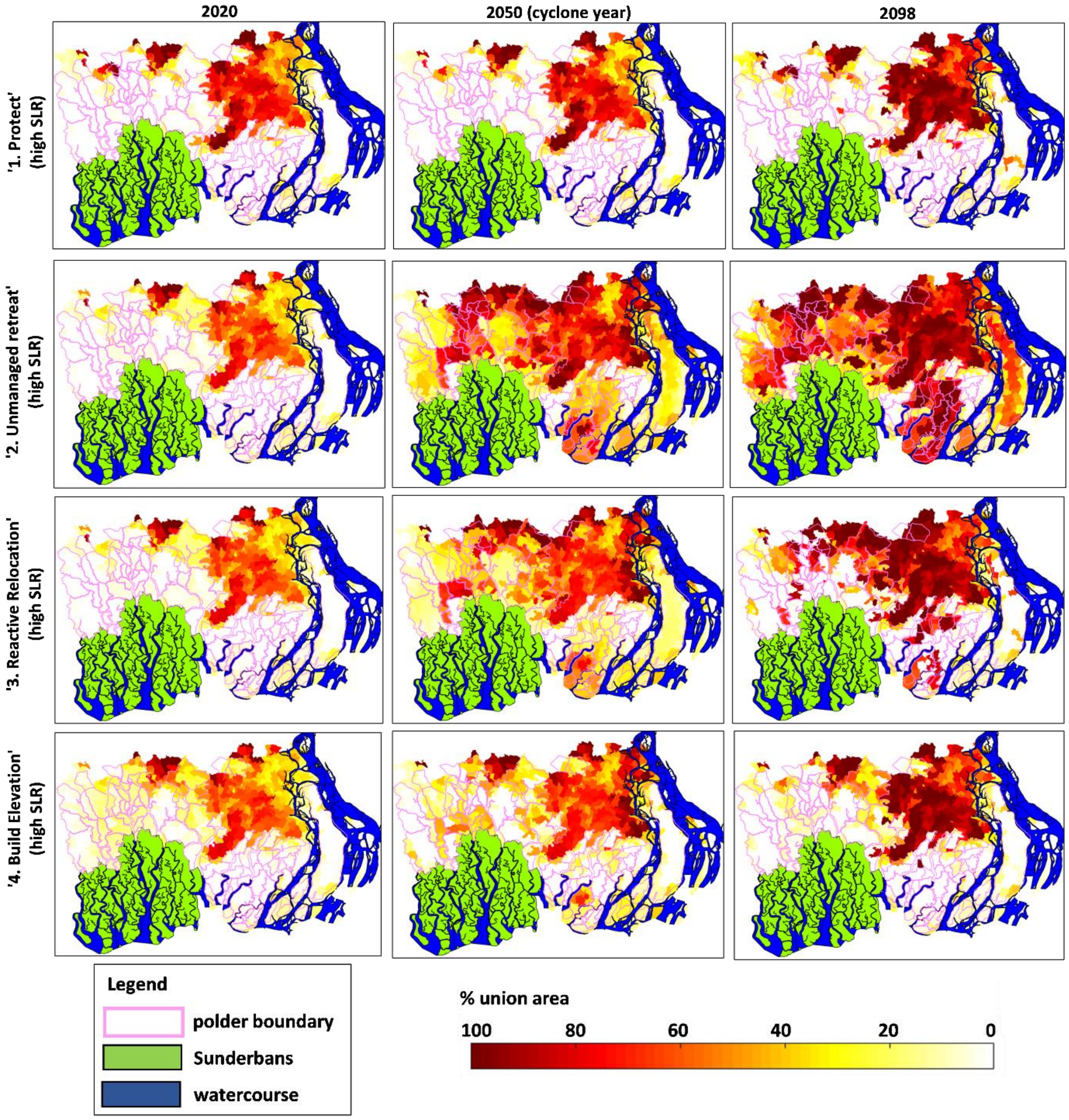


Figure S2: Maximum union inundation area (percent) in three time slices under high sea level rise and the four development trajectories

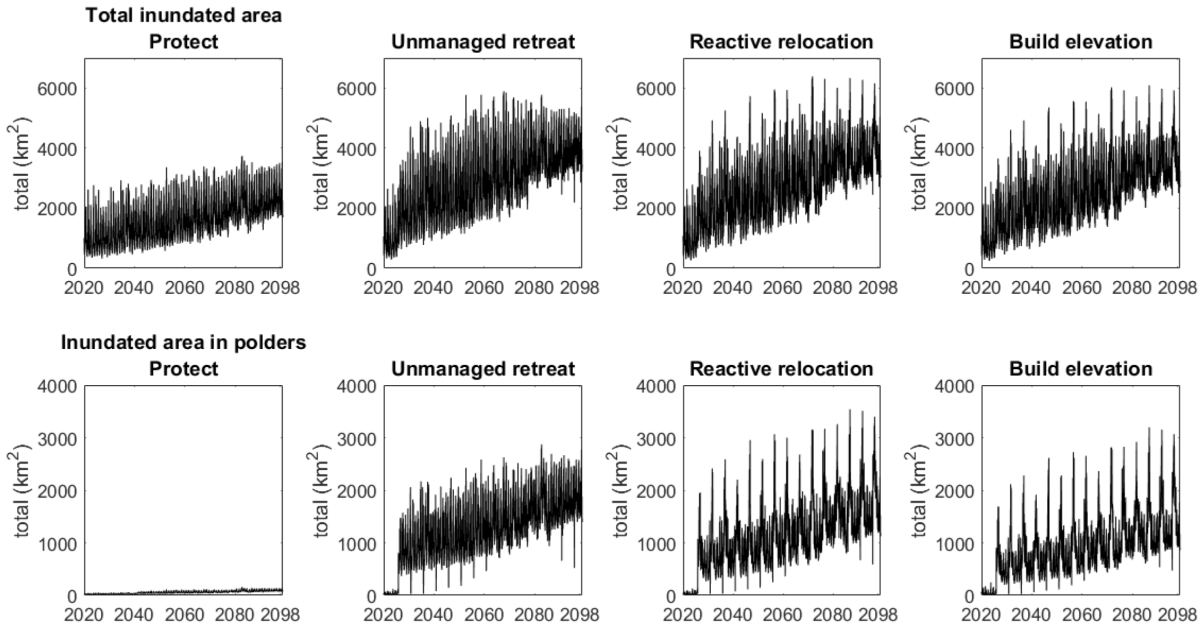


Figure S3a: Daily inundation area (km^2) under low sea level rise for the study area (top row) and for only the poldered areas (bottom row)

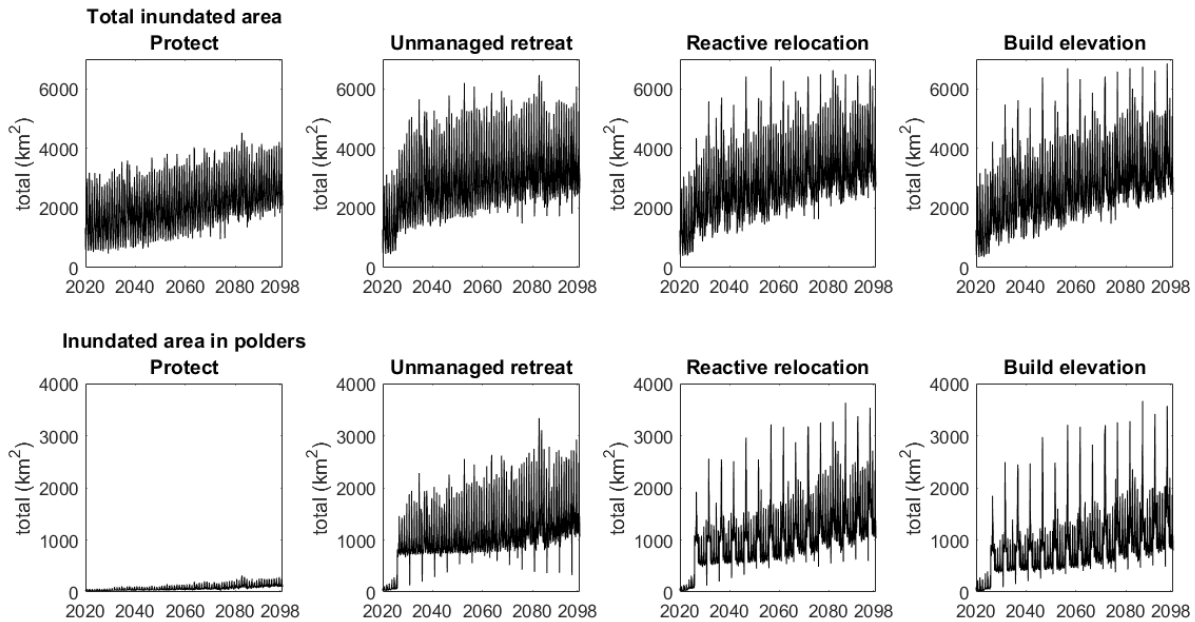


Figure S3b: Daily inundation area (km^2) under high sea level rise for the study area (top row) and for only the poldered areas (bottom row)

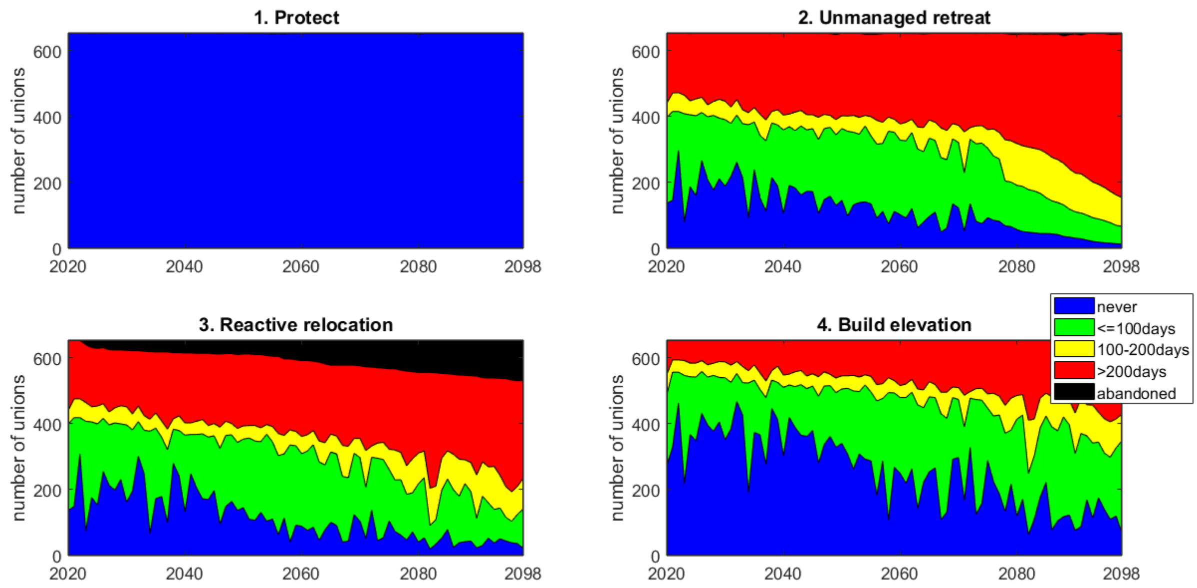


Figure S4a: Number of waterlogged unions with different number of waterlogging length under low sea level rise and development trajectories

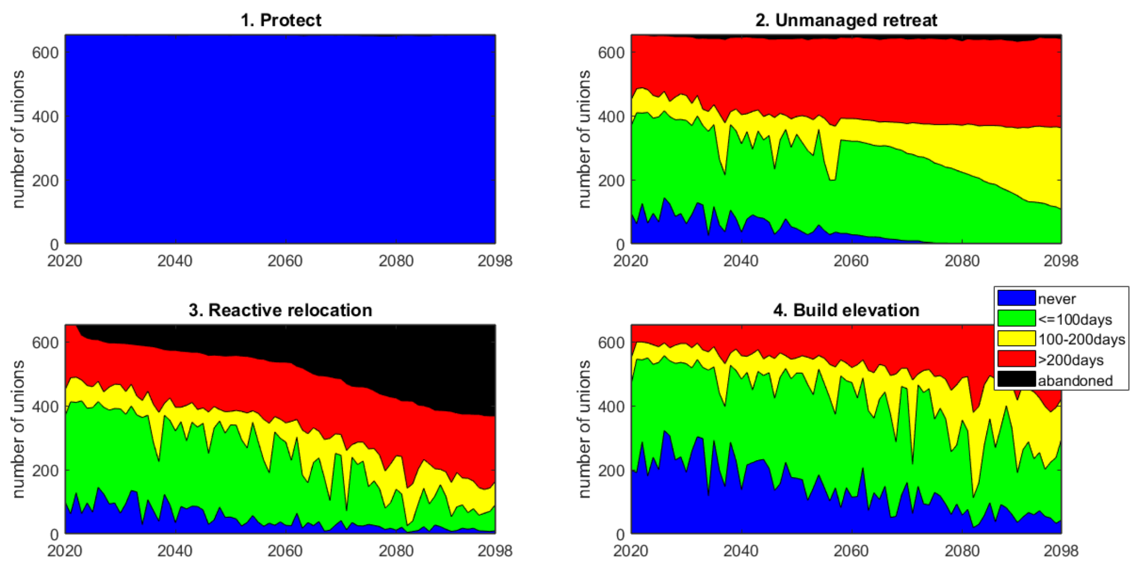


Figure S4b: Number of waterlogged unions with different number of waterlogging length under high sea level rise and development trajectories

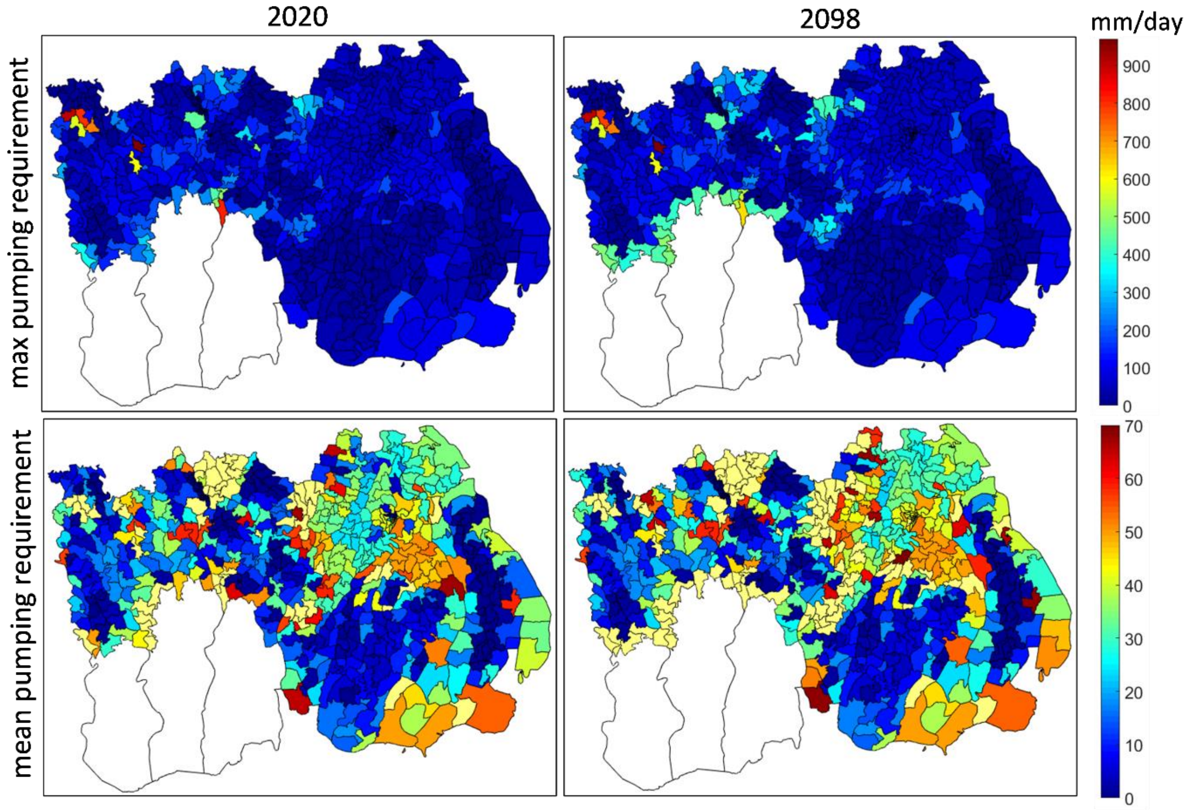


Figure S5a: Pumping requirement of '1. Protect' scenario under low sea level rise

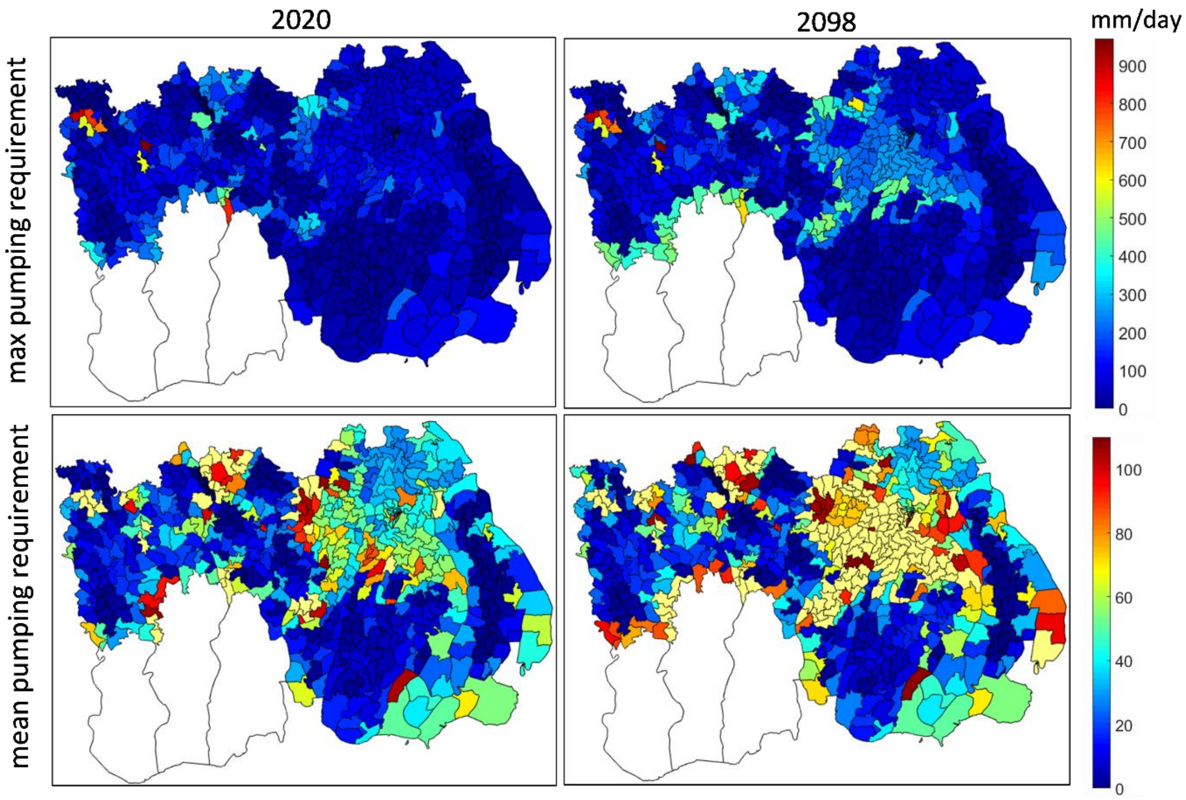


Figure S5b: Pumping requirement of '1. Protect' scenario under high sea level rise

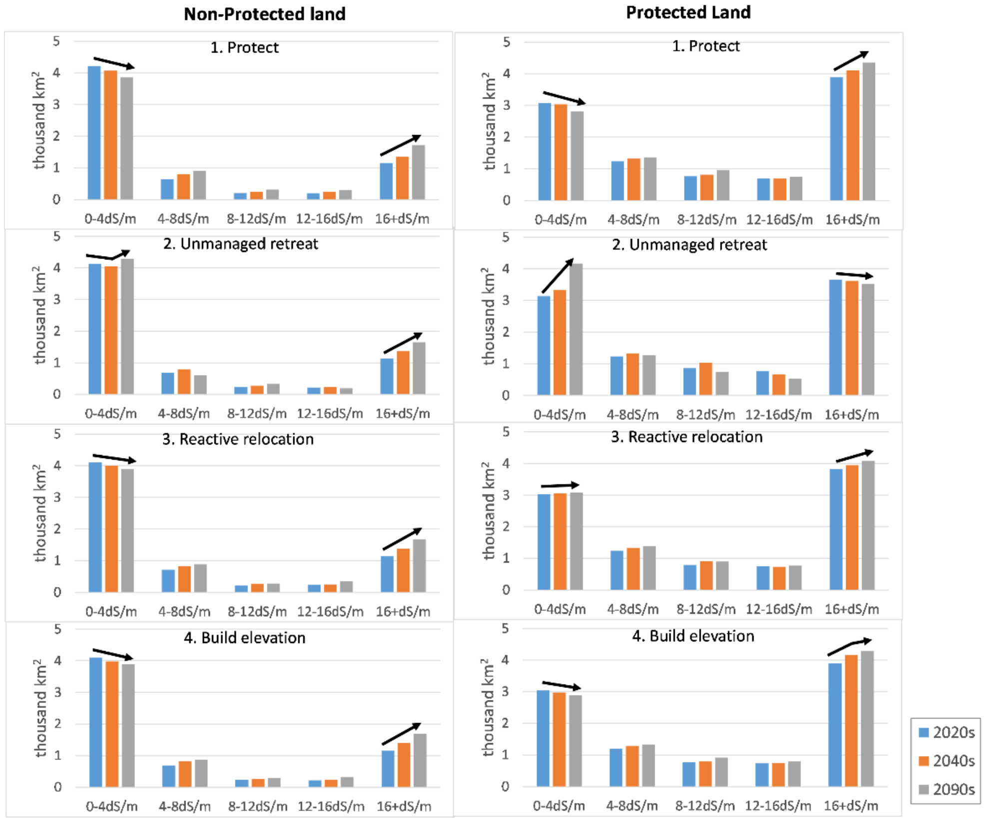


Figure S6a: Total land area belonging to different annual maximum soil salinity categories under low Sea Level Rise – low Development

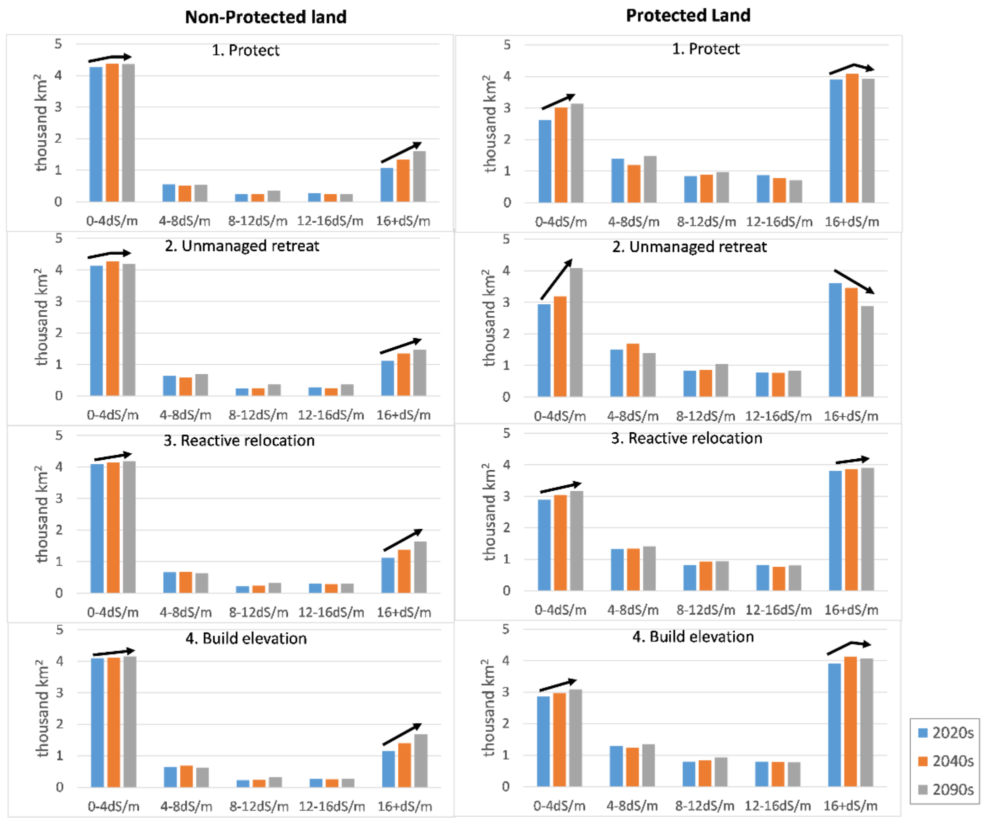


Figure S6b: Total land area belonging to different annual maximum soil salinity categories under high Sea Level Rise - low Development

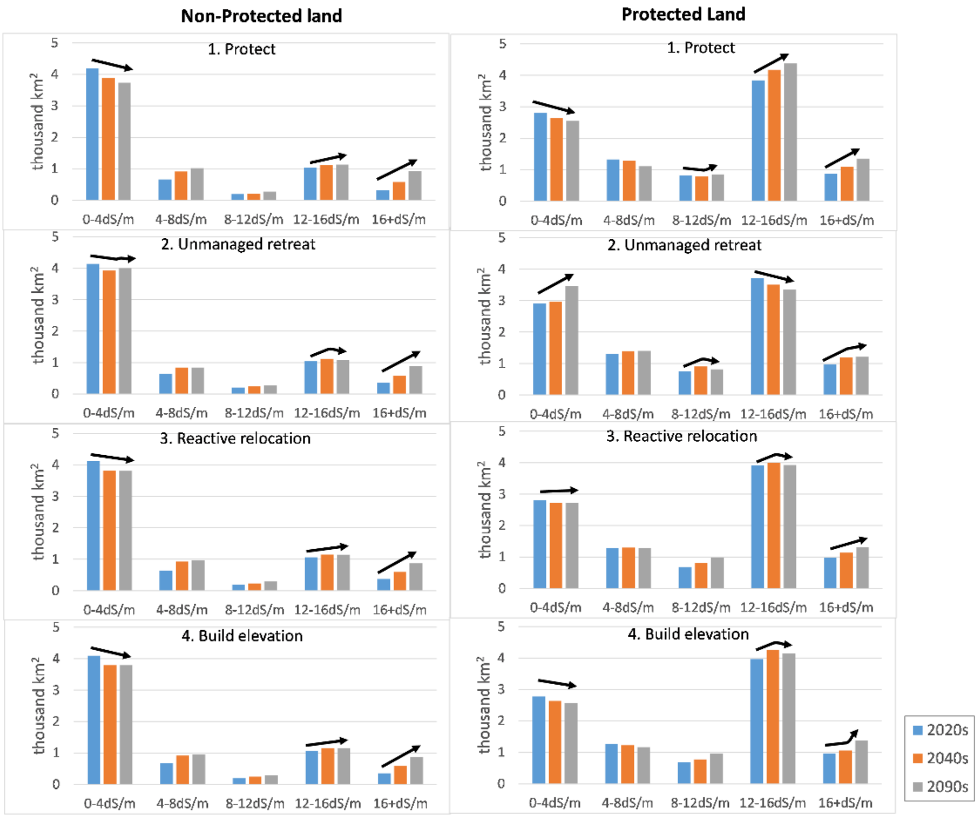


Figure S7a: Total land area belonging to different annual maximum soil salinity categories under low Sea Level Rise – high Development

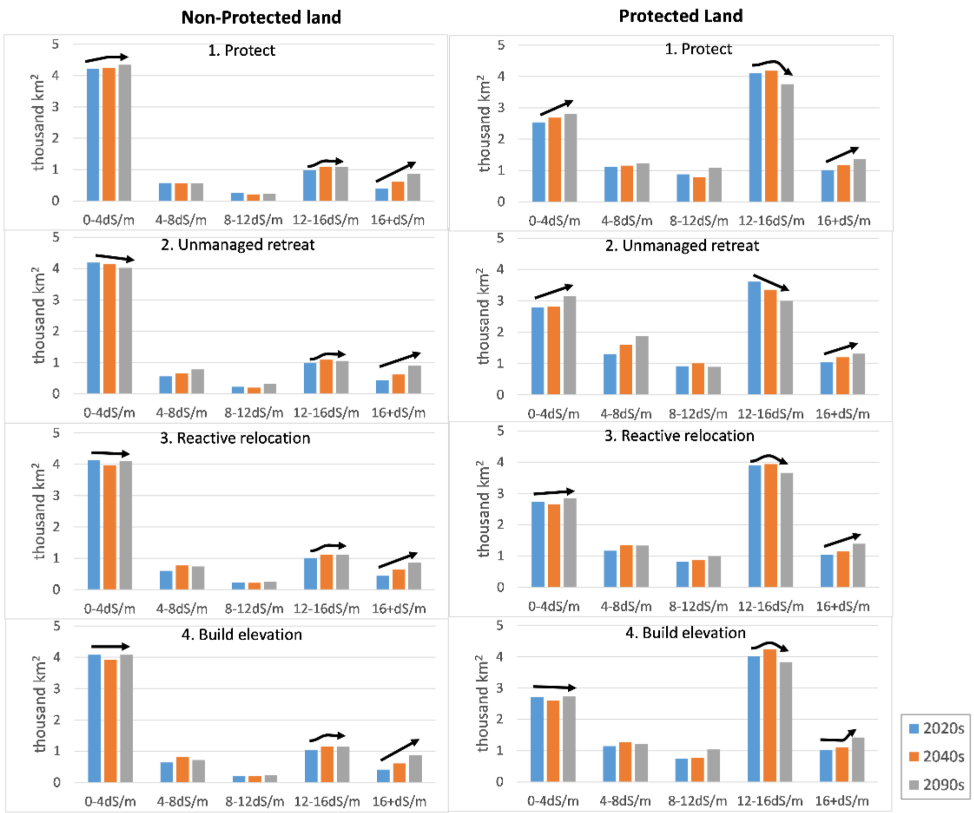


Figure S7b: Total land area belonging to different annual maximum soil salinity categories under high Sea Level Rise – high Development

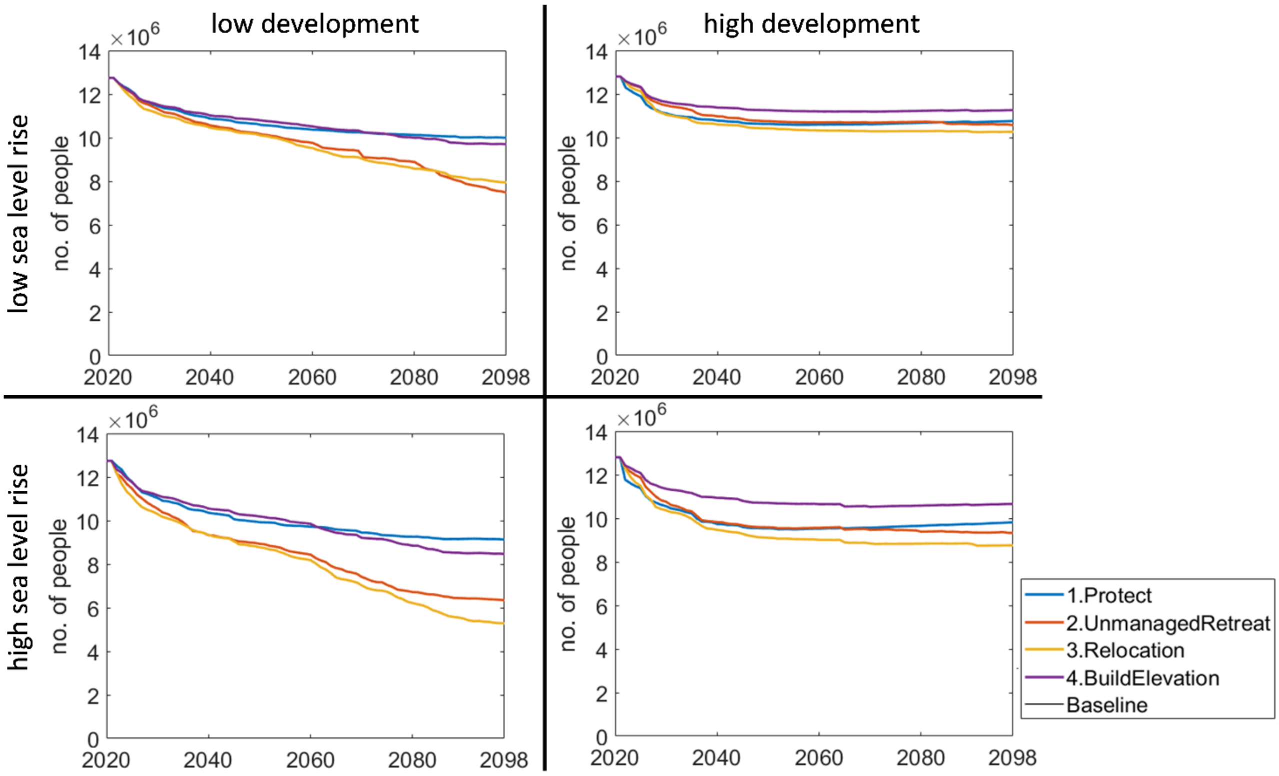


Figure S8: Total rural population under all climate and development scenarios and development trajectories

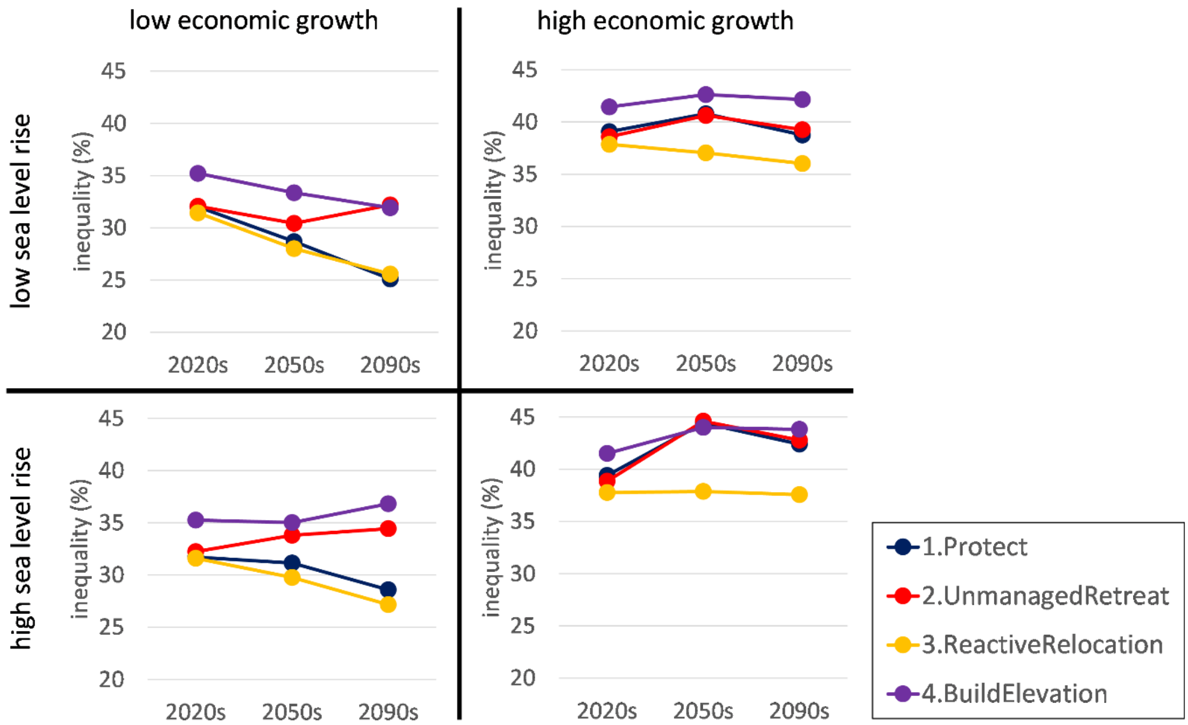


Figure S9: Income inequality (GINI index) under all climate and development scenarios and development trajectories

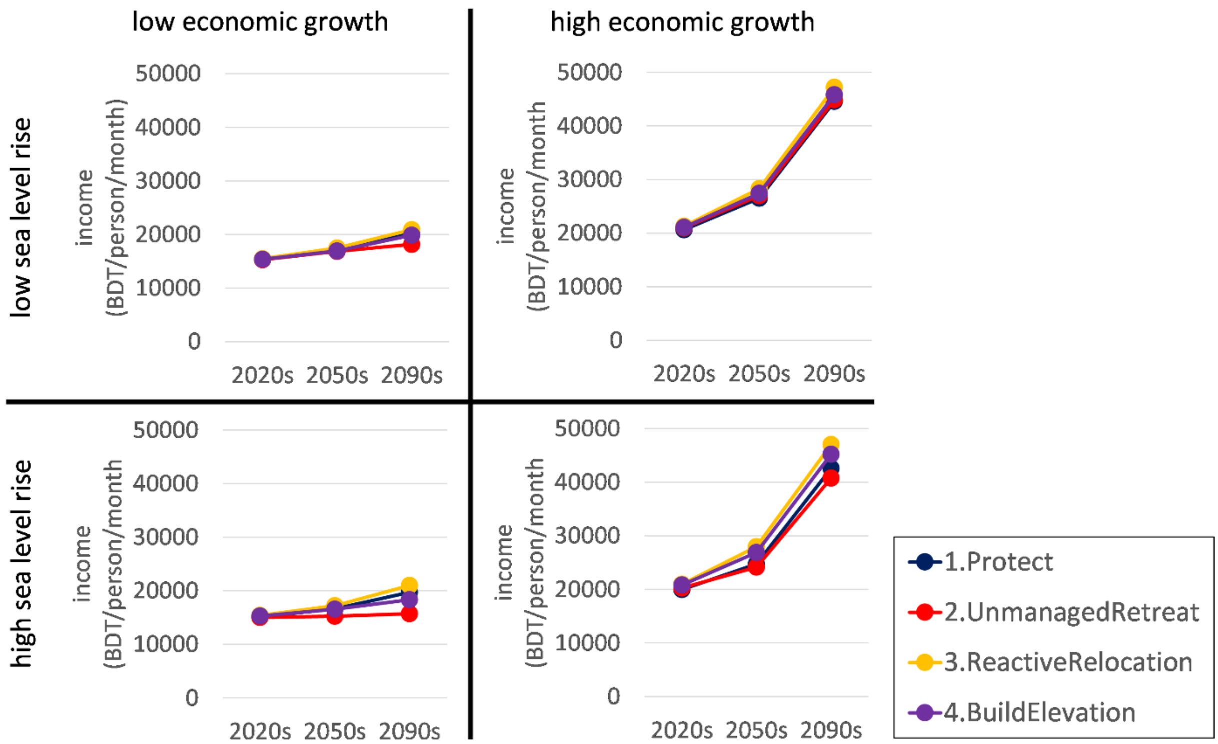


Figure S10: Mean household income under all climate and development scenarios and development trajectories

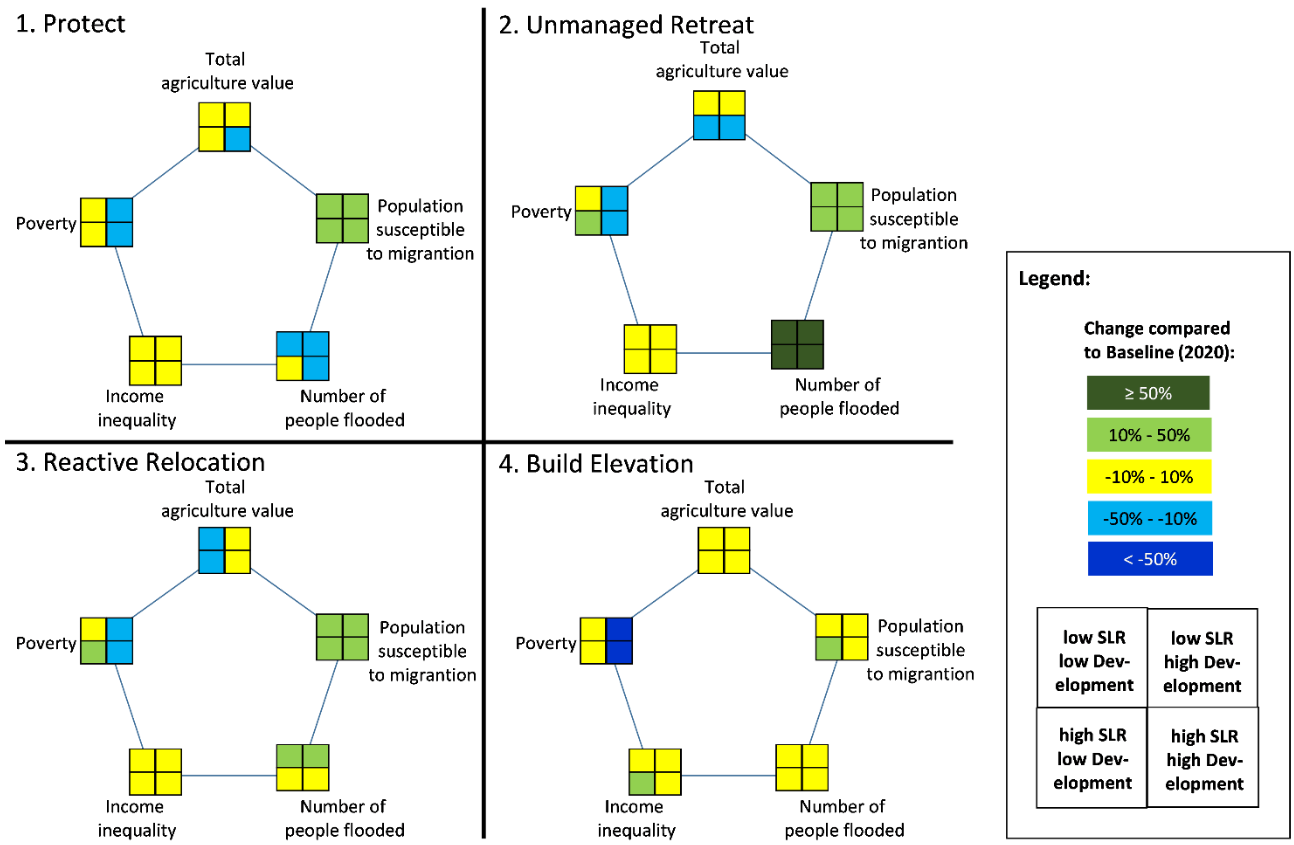
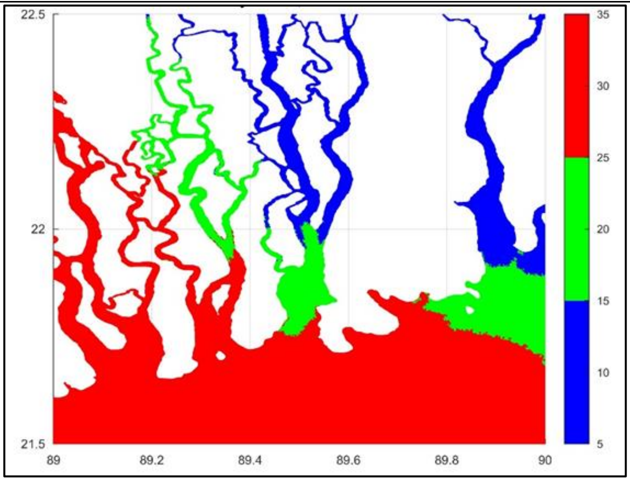
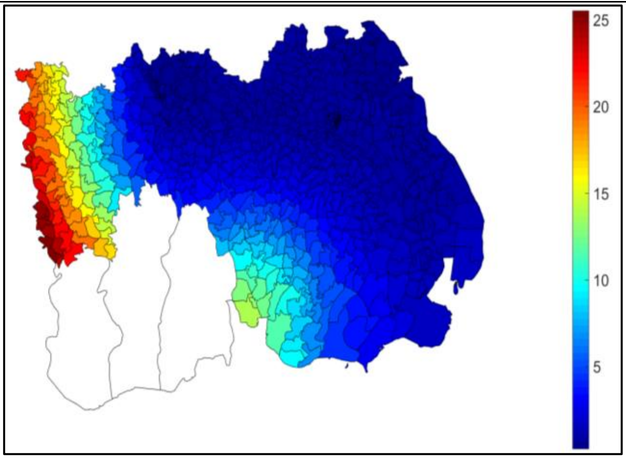


Figure S11: Overview of changes (2020-2050) in key outputs under all climate and development scenarios and development trajectories



FVCOM river salinity results used as 'true' to train emulators (ppt, Q0 BaU scenario, year 2000)



ΔDIEM emulated river salinity Union level (ppt, Q0 BaU scenario, year 2000) (Payo et al., 2017)

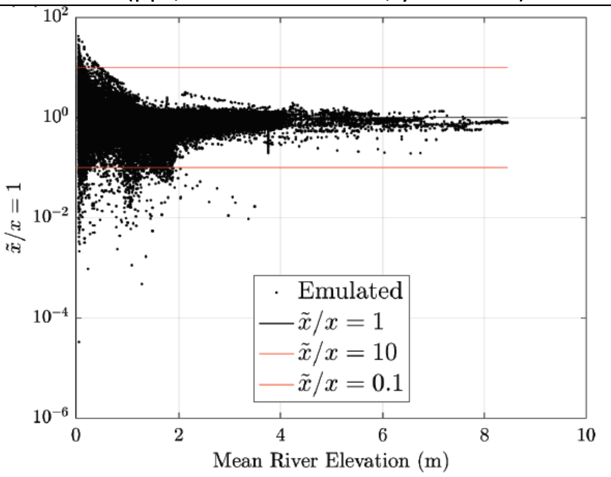


Figure 5. Linear emulators of mean water level in the river: (b) large emulated mean river elevation are well within the uncertainty band of factor 10 of simulated values. (Payo et al., 2017)

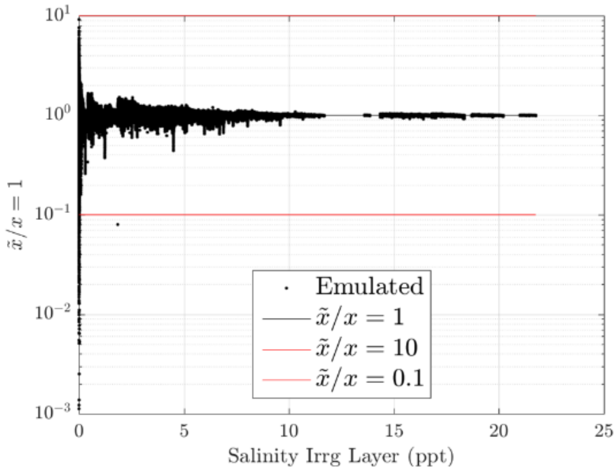
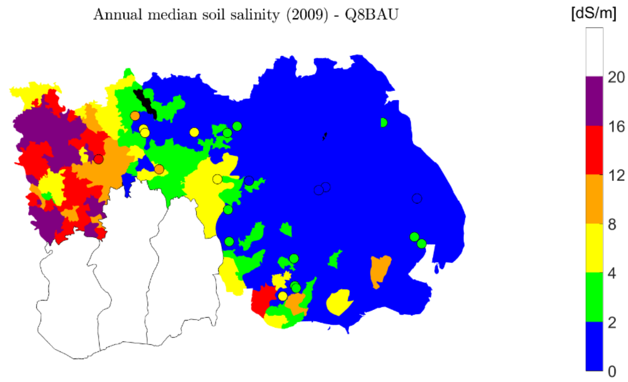
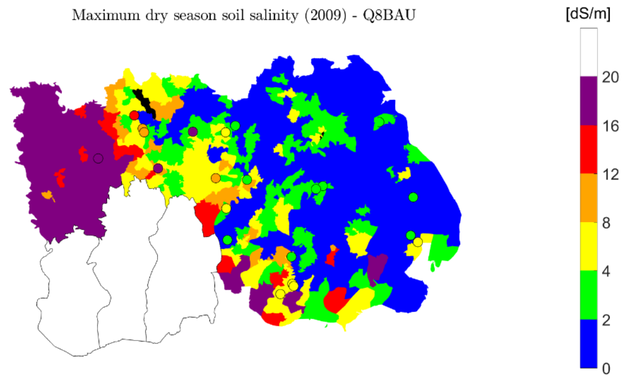


Figure 31.A1: Accuracy of groundwater salinity emulator in ΔDIEM at ~100m depth (right panels). (x: simulated value; $\hat{x}$: emulated value) (Lázár et al., 2018)



Annual median soil salinity (dS/m) - 2009
Observations: Dasgupta et al. (2015)



Annual maximum soil salinity (dS/m) – 2009
Observations: Dasgupta et al. (2015)

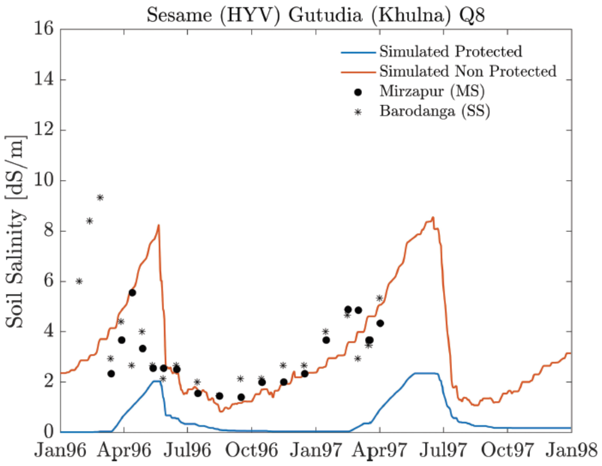


Figure 7. The proposed soil salinity model can reproduce the observed daily variability reported by Mondal et al. [2001] for sesame farming during the period 1996–1998 if salt flux from flooding is considered. (Payo et al., 2017)

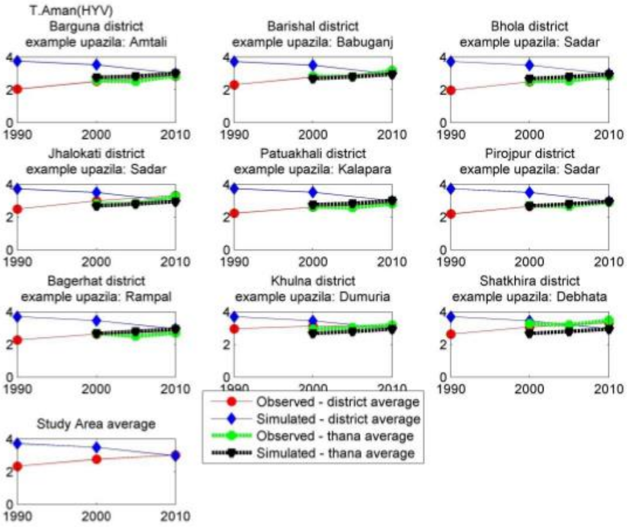


Figure S3.1: Observed and simulated yield (tons/ha) of Transplanted Aman (HYV) (Lazar et al., 2015)

Figure S12: Selected ΔDIEM model performance comparisons (bio-physical)

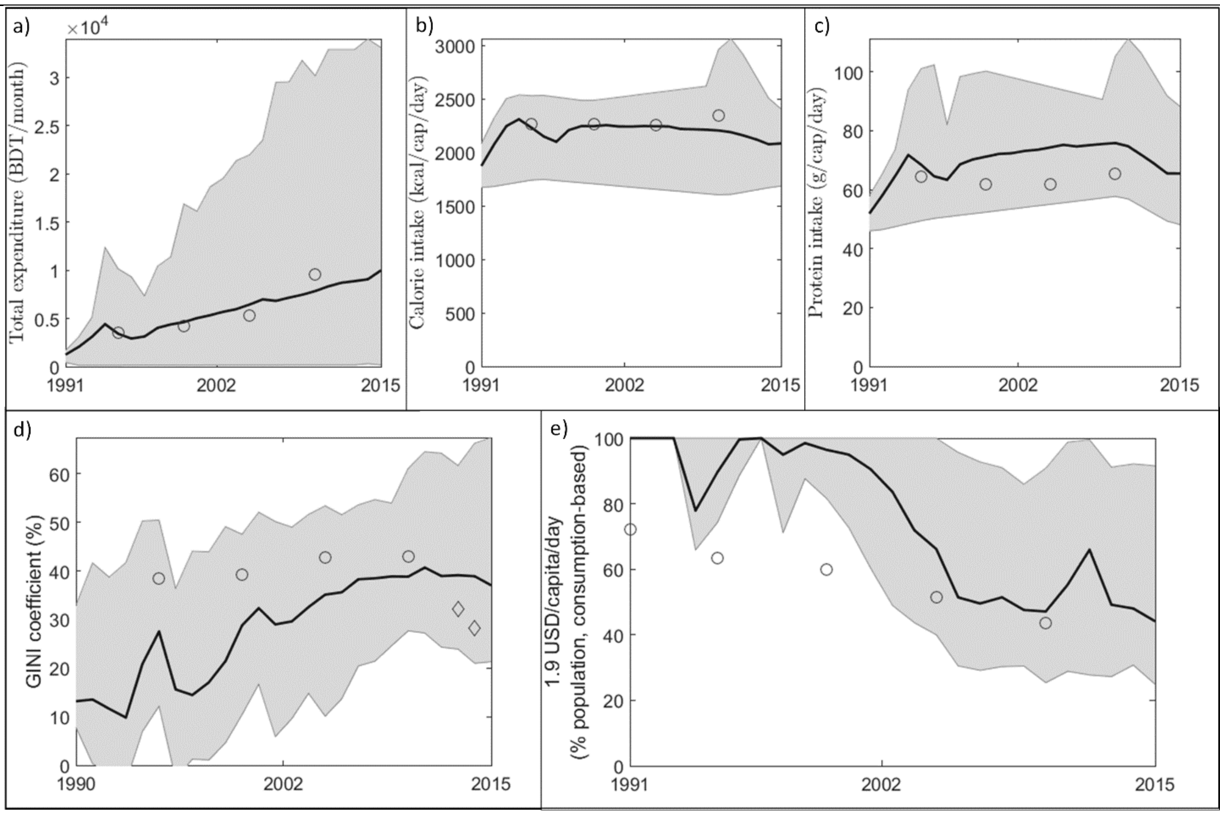


Figure 28.A4 Validation of the process-based household component of ΔDIEM (Lázár et al., 2018) Black lines show the simulated mean study area values, shaded area shows the min-max simulated range within the study area, and grey dots and diamonds are observations. Observations: a) BBS (2011) Table 4.4; b) BBS (2011) Table 5.3; c) BBS (2011) Table 5.4; d) dots: rural inequality: Ferdousi and Dehai (2014), Diamonds: national inequality - UNDP (http://hdr.undp.org/en/content/income-gini-coefficient accessed on 08/07/2016); e) World Bank: People living on less than $1.90 a day (http://povertydata.worldbank.org/poverty/country/BGD accessed on 08/07/2016)

Figure S13: Selected ΔDIEM model performance comparisons (socio-economic)

Table S1: Household archetypes based on the seasonally dominant livelihood and land size (based on the ESPA Deltas' household survey)

Archetype ID	Seasonally dominant livelihood (Season 1 – Season 2 – Season 3) (February-June; June-October; October-February)	Cumulative occurrence (%)	No. of households: Landless / Home-stead (LL:<0.5acres)	Small Land Owner (SLO: 0.5-2.5 acres)	Large Land Owner (LLO: >2.5 acres)
1	SmallBusiness – SmallBusiness – SmallBusiness	19	103	157	24
2	CottageIndustry – CottageIndustry – CottageIndustry	33	132	72	0
3	FarmOwner – FarmOwner – FarmOwner	38	9	43	20
4	Fisher – Fisher – Fisher	42	42	20	0
5	CottageIndustry – FarmLabour – CottageIndustry	45	32	10	0
6	CottageIndustry – SmallBusiness – SmallBusiness	47	17	18	0
7	SmallBusiness – SmallBusiness – CottageIndustry	49	15	17	0
8	SmallBusiness – SmallBusiness – FarmOwner	52	0	25	7
9	FarmOwner – CottageIndustry – CottageIndustry	53	9	15	0
10	FarmOwner – noJob – FarmOwner	55	0	24	0
11	CottageIndustry – SmallBusiness – CottageIndustry	56	13	10	0
12	FarmOwner – SmallBusiness – FarmOwner	58	0	23	0
13	CottageIndustry – Fisher – CottageIndustry	59	14	8	0
14	FarmOwner – SmallBusiness – SmallBusiness	61	0	22	0
15	SmallBusiness – CottageIndustry – SmallBusiness	62	11	10	0
16	CottageIndustry – CottageIndustry – SmallBusiness	64	8	12	0
17	FarmLabour – CottageIndustry – CottageIndustry	65	20	0	0
18	FarmLabour – FarmLabour – CottageIndustry	66	20	0	0
19	SmallBusiness – CottageIndustry – CottageIndustry	68	8	11	0
20	Forest Good Collector	68	11	0	0

Table S2: Development trajectory assumptions

<table>
<tr><th>Policy strategy</th><th>Description</th><th>Embankments</th><th>Infrastructure repair time</th><th>Migration</th></tr>
<tr><td>1. ‘Protect’</td><td>This scenario assumes large investments in enhanced flood embankments and drainage systems to adapt to the growing risks of SLR like occurs in the Netherlands. Water pumping ensures that waterlogging never happens.</td><td>+3m above current height throughout the simulation</td><td>short, only 6 months after dike failure</td><td>autonomous relocation (see assumptions in text)</td></tr>
<tr><td>2. ‘Unmanaged retreat’</td><td>This scenario explores the implications of practically no investment in protection or adaptation to SLR in the coastal zone. It provides a baseline assessment of the potential impacts of climate change in the absence of governance.</td><td>embankments progressively deteriorate at a rate of -5cm/year (-4m by 2100)</td><td>long, 60 months after dike failure</td><td>autonomous relocation</td></tr>
<tr><td>3. ‘Reactive relocation’</td><td>This scenario envisages some government action to cope with the growing pressures of climate and environmental change, with an emphasis upon relocation of coastal communities. Abandonment in reality is rare and motivated to prevent the loss of life and exposure to hazard, or loss of livelihood (Hino et al., 2017, Jha, 2010).</td><td>maintained at current level until relocation occurs</td><td>18 months, unless the polder is abandoned (i.e. all people are moved away)</td><td>relocation of entire communities after 50% of population have moved away based on individual migration decisions</td></tr>
<tr><td rowspan="2">4. ‘Build elevation’</td><td>This scenario envisages working with natural processes to naturally deposit sediment through controlled flooding termed as Tidal River Management (TRM) in Bangladesh (Gain et al., 2017, Mutahara et al., 2017, van Staveren et al., 2016). TRM is only exercised in selected locations at present.</td><td>maintained at current level</td><td>18 months, similar to what happened after the SIDR cyclone in Polder 32</td><td>autonomous relocation</td></tr>
<tr><td colspan="4">Here, the maximum benefit of TRM is explored by implementing it in all polders simultaneously (Darby et al., 2018). TRM starts in 2020, lasts for 5 years, covers 20% of the polder area and operates when river salinity is ≤10 ppt. Assumed daily sedimentation rate (when inundation occurs) is 0.42 $cmday^{-1}$ and 0.21 $cmday^{-1}$ for the cut- and furthest points of the TRM area, respectively (calculated from Amir et al., 2013). Sedimentation updates the union hypsometric curves (elevation-cumulative area curves), the drainage rates and flooding area/depth in ΔDIEM. Compensation for farm-based households: 1000 $BDTyear^{-1}ha^{-1}$ (~12 $USDyear^{-1}ha^{-1}$) during TRM years.</td></tr>
</table>

Table S3: Land Cover and Land Use changes by 2050

Land cover classes	Less sustainable	More Sustainable
Agriculture	- Agriculture land is abandoned (by 20% in the highly saline areas and by 10% in the moderately saline areas) due to high salinity levels. - Rice is the dominant crop (few other crops: as in 1990) - Very few new crops compared to present (i.e. no better yielding and higher salt tolerance varieties – present crops).	- Slightly smaller agriculture area (-5%) that was given up to protect certain areas (mangrove and non-mangrove land cover). - Rice still dominant, but more cash-crops (e.g. vegetables) and high yielding varieties - Use of deep groundwater irrigation and drinking water wells to minimise salinity impact - Targeted subsidy programs to promote land use zoning (30% increase in area if agriculture is promoted) - Several new crops with higher yield and higher salt tolerance.
Aquaculture	- Saltwater shrimp area increases from Sundarbans clearings. - Freshwater prawn production is negligible. The land is either abandoned or rice is produced instead of aquaculture.	- Saltwater shrimp area same, but more sustainable management - Targeted subsidy programs to promote land use zoning (30% increase in area if aquaculture is promoted)
Mangrove	- Decreased area everywhere (-10%) for more agriculture land and aquaculture areas. - Significant encroachment in Sundarbans (-20%) to turn land to shrimp production areas.	- Increased mangrove area especially along the coast (converted from agriculture). - Targeted subsidy programs to promote land use zoning (20% increase in area if tourism is promoted)
Non-mangrove vegetation	- Decreased area everywhere (-10%) for more agriculture land and aquaculture areas.	- Slightly increased area (converted from agriculture).
Rural settlement	- No change	- Less settlements on floodplains (less damage, but no overall change in % settlement area within the unions) - Targeted subsidy programs to promote land use zoning (10% increase in area if tourism is promoted)
Urban settlement	- No change	- Less settlements on floodplains (less damage, but no overall change in % settlement area within the unions) - Targeted subsidy programs to promote land use zoning (30% increase in area if urbanisation is promoted)
Wetland/Mudflat/ Sand/Bare land	- increase from abandoned agriculture land	- No change
Water Surface Area	- No change	- No change

Table S4: Mean decadal total rice produce (tons)

		low development			high development		
		2020s	2040s	2090s	2020s	2040s	2090s
low sea level rice	1.Protect	1,397,712	1,262,277	1,103,327	3,696,565	3,456,877	9,582,366
	2.unmanagedRetreat	1,350,640	1,223,197	601,630	3,740,254	3,563,375	9,785,443
	3.ReactiveRelocation	1,339,000	1,195,062	876,408	3,710,778	3,537,338	9,783,060
	4.BuildElevation	1,384,823	1,295,246	1,037,468	3,803,982	3,654,071	10,133,576
	Baseline	1,346,975	1,222,640	902,558	3,728,650	3,558,994	10,000,587
		2020s	2040s	2090s	2020s	2040s	2090s
high sea level	1.Protect	1,336,496	1,177,270	1,008,969	3,682,656	3,233,701	8,996,718
	2.unmanagedRetreat	1,248,897	892,847	312,743	3,425,848	2,628,201	7,495,878
	3.ReactiveRelocation	1,245,193	980,439	532,894	3,467,754	3,051,418	8,799,570
	4.BuildElevation	1,332,701	1,178,695	753,205	3,662,008	3,379,724	9,785,355
	Baseline	1,274,063	1,060,481	578,421	3,506,995	3,109,109	9,209,168

Table S5: Cost of Tidal River Management in Bangladesh

Source	Location	cost (million BDT)	area (ha)	million BDT/ha
Gain et al. (2017)	Beel Pakhimara	2620	700	3.74
	Beel Khukshia	33.4	1170	0.03
Amir et al. (2013)	East Beel Khuksia	285.85	900	0.32
	East Beel Khuksia	213.46	900	0.24
	East Beel Khuksia	355.84	900	0.40
	Beel Kapalia	207.99	625	0.33
	Beel Kapalia	161.67	625	0.26
	Beel Kapalia	252.17	625	0.40
			Mean:	***0.71***

Table S6: Evaluation of development trajectories

	Direct capital & maintenance cost (billion BDT)
1. Protect	1080-2080*
2. Unmanaged retreat	0
3. Reactive relocation	458-1194**
4. Build elevation	219***

Notes:

* **Cost = dike improvement + dike maintenance.** There are 5000 km dikes in the study area, +3m increase in embankment height, dike raising cost: 0.7-1.2 million EUR/km/m (Table 2 for Vietnam, Jonkman et al., 2013). Dike maintenance: 0.02 million EUR/km/year (1 EUR = 100 BDT, 80 years => 80 billion BDT by 2100) (Table 2 for Vietnam, Jonkman et al., 2013).

** **Cost = relocation + dike maintenance.** The relocated people are between 0.44 and 1.66 million based on the simulations. Hino et al. (2017) estimates relocation cost for Fiji and UK Coastal Change Pathfinder as US$10,000 per person. 1 US$ = 85 BDT (17 October 2018 exchange rate). Dike maintenance: 0.02 million EUR/km/year (1 EUR = 100 BDT, 80 years => 80 billion BDT by 2100) (Table 2 for Vietnam, Jonkman et al., 2013).

*** **Cost = TRM + dike maintenance + compensation**. Total poldered areas of the study area (ha) is 976,496 ha. Only 20% is for impacted by TRM that is 195,299ha. Average cost of TRM is 0.71 million BDT/ha (see Table S2). Dike maintenance: 0.02 million EUR/km/year (1 EUR = 100 BDT, 80 years => 80 billion BDT by 2100) (Table 2 for Vietnam, Jonkman et al., 2013). The total agriculture land in the poldered areas is 559 thousand hectare, of which 111 thousand hectare (20 percent) is used during the TRM. By considering the 1000 BDT/ha/year compensation, this would cost the government 111,000 ha * 1000 BDT/ha * 5 years = 555 million BDT

Table S7: Comparison of key bio-physical outputs with literature values

Output variable	Simulated result	Literature values
Total inundation area	500 to 3000 km^2 (monsoon flooding); <6000km^2 (cyclone flooding)	for the entire coastal zone of Bangladesh (ca. 30% larger area): • 5510 km^2 (Mohal and Hossain, 2007) • 4107 km^2 (WARPO, 2005) for Khulna and Barisal districts only • 4356 km^2 (monsoon flooding, CCC, 2009b) • ca. 12,000 km^2 (cyclone flooding, CCC, 2009a)
Soil salinity (km^2)	8700 km^2 (year 2020)	• 8317.7 km^2 (calculated for our study area, year 2009, SRDI, 2012)
Dry season soil salinity (% change)	7-21%	• 39.2% by 2050 (Dasgupta et al., 2015) • 39% (+3277 km^2) by 2100 (Mohal and Hossain, 2007)
Rice produce	3.6 million tons (year 2020, modern crop varieties)	• 3.56 million tons (Aus, Aman, Boro) for our study area (BBS, 2012).

Table S8: Sensitivities of different outputs to different drivers

In a local sensitivity analysis, the mean decadal simulated values (2089-2098) were compared with a baseline value (2015-24) for 36 plausible scenarios. The maximum range of the sensitivities was calculated for each driver and then normalised.

Mean of simulations	inundation (km2)	soil salinity (dS/m)	Rice (tons)	GINI (%)	Poverty (%)	GDP/capita (BDT/month)
climate	high	very high	low	low	low	low
relative SLR	high	low	low	low	low	low
cyclone intensity	high	moderate	low	low	low	low
polder maintenance	very high	low	low	low	low	low
population size	low	low	low	moderate	low	very high
micro economy	low	low	low	moderate	very high	high
land cover	low	low	low	low	low	low
farming practices	low	very high	very high	very high	low	moderate

Note: Sensitivity classes: low (0-24%), moderate (25-49%), high (50-74%), very high (75-100%)

References

AMIR, M. S. I. I., KHAN, M. S. A., KHAN, M. M. K., RASUL, M. G. & AKRAM, F. 2013. Tidal River Sediment Management–A Case Study in Southwestern Bangladesh. *International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering,* 7**,** 175-185.

BBS 2011. Report of the Household Income & Expenditure Survey 2010. Bangladesh Bureau of Statistics, Statistical Division, Ministry of Planning.

BBS 2012. Yearbook of Agricultural Statistics of Bangladesh - 2012. 24th ed. Bangladesh Bureau of Statistics: Statistics and Informatics Division, Ministry of Planning, Government of the People's Republic of Bangladesh.

CCC 2009a. Climate Change Research. Characterizing Country Settings: Development of a Base Document in the Backdrop of Climate Change Impacts. Climate Change Cell, Department of Environment, Ministry of Environment and Forests; Component 4b, CDMP, MoFDM. Month 2009, Dhaka.

CCC 2009b. Impact Assessment of Climate Change and Sea Level Rise on Monsoon Flooding. Climate Change Cell, Department of Environment, Ministry of Environment and Forests; Component 4b, CDMP, MoFDM. Month 2009, Dhaka.

DARBY, S., NICHOLLS, J. R., RAHMAN, M., BROWN, S. & KARIM, R. 2018. A Sustainable Future Supply of Fluvial Sediment for the Ganges-Brahmaputra Delta. *In:* NICHOLLS, R. J., HUTTON, C. W., ADGER, W. N., HANSON, S., RAHAMAN, M. & SALEHIN, M. (eds.) *Ecosystem Services For Well-Being In Deltas: Integrated Assessment For Policy Analysis.* Palgrave, ISBN 978-3-319-71092-1.

DASGUPTA, S., HOSSAIN, M. M., HUQ, M. & WHEELER, D. 2015. Climate change and soil salinity: The case of coastal Bangladesh. *Ambio,* 44**,** 815-826.

FERDOUSI, S. & DEHAI, W. 2014. Economic Growth, Poverty and Inequality Trend in Bangladesh. *Asian Journal of Social Sciences & Humanities,* 3**,** 1-11.

GAIN, A. K., BENSON, D., RAHMAN, R., DATTA, D. K. & ROUILLARD, J. J. 2017. Tidal river management in the south west Ganges-Brahmaputra delta in Bangladesh: Moving towards a transdisciplinary approach? *Environmental Science & Policy,* 75**,** 111-120.

HINO, M., FIELD, C. B. & MACH, K. J. 2017. Managed retreat as a response to natural hazard risk. *Nature Clim. Change,* 7**,** 364-370.

JHA, A. K. 2010. Chapter 5: Assessing Damage and Defining Reconstruction Policy to relocate or not to relocate. *Safer Homes, Stronger Communities.* World Bank, January 2010, doi: 10.1596/978-0-8213-8045-1.

JONKMAN, S. N., HILLEN, M. M., NICHOLLS, R. J., KANNING, W. & VAN LEDDEN, M. 2013. Costs of Adapting Coastal Defences to Sea-Level Rise— New Estimates and Their Implications. *Journal of Coastal Research***,** 1212-1226.

LAZAR, A. N., CLARKE, D., ADAMS, H., AKANDA, A. R., SZABO, S., NICHOLLS, R. J., MATTHEWS, Z., BEGUM, D., SALEH, A. F. M., ABEDIN, M. A., PAYO, A., STREATFIELD, P. K., HUTTON, C., MONDAL, M. S. & MOSLEHUDDIN, A. Z. M. 2015. Agricultural livelihoods in coastal Bangladesh under climate and environmental change - a model framework. *Environmental Science: Processes & Impacts,* 17**,** 1018-1031.

LÁZÁR, A. N., PAYO, A., ADAMS, H., AHMED, A., ALLAN, A., AKANDA, A. R., JOHNSON, F. A., BARBOUR, E. J., BISWAS, S., CAESAR, J., CHAPMAN, A., CLARKE, D., FERNANDES, J. A., HAQUE, A., HOSSAIN, M., HUNT, A., HUTTON, C. W., KAY, S., MUKHOPADHYAY, A., NICHOLLS, J. R., SALEH, A. F. M., SALEHIN, M., SZABO, S. & WHITEHEAD, P. 2018. Integrative analysis applying the Delta Dynamic Integrated Emulator Model in south-west coastal Bangladesh. *In:* NICHOLLS, R. J., HUTTON, C. W., ADGER, W. N., HANSON, S., RAHAMAN, M. & SALEHIN, M. (eds.) *Ecosystem Services For Well-Being In Deltas: Integrated Assessment For Policy Analysis.* Palgrave, ISBN 978-3-319-71092-1.

MOHAL, N. & HOSSAIN, M. M. A. 2007. Investigating the impact of relative sea level rise on coastal communities and their livelihoods in Bangladesh. Draft Final Report. . Dhaka: Institute of Water Modelling (IWM) and Center for Environmental and Geographic Information Services (CEGIS). Submitted to UK Department for Environment Food and Rural Affairs in May 2007.

MUTAHARA, M., WARNER, J. F., WALS, A. E. J., KHAN, M. S. A. & WESTER, P. 2017. Social learning for adaptive delta management: Tidal River Management in the Bangladesh Delta. *International Journal of Water Resources Development***,** 1-21.

PAYO, A., LÁZÁR, A. N., CLARKE, D., NICHOLLS, R. J., BRICHENO, L., MASHFIQUS, S. & HAQUE, A. 2017. Modeling daily soil salinity dynamics in response to agricultural and environmental changes in coastal Bangladesh. *Earth's Future,* 5**,** 495–514.

SRDI 2012. *Saline Soils of Bangladesh,* Farmgate, Dhaka, Bangladesh, Soil Resource Development Institute, Ministry of Agriculture.

VAN STAVEREN, M. F., WARNER, J. F. & SHAH ALAM KHAN, M. 2016. Bringing in the tides. From closing down to opening up delta polders via Tidal River Management in the southwest delta of Bangladesh. *Water Policy*.

WARPO 2005. Impact Assessment of Climate Change on the Coastal zone of Bangladesh. Water Resources Planning Organization (WARPO), Dhaka, Bangladesh.